Mon. Not. R. Astron. Soc. **000**, 1–7 (19xx) Printed 5 February 2008 (MN LATEX style file v1.4)

A comprehensive search for extragalactic 6.7-GHz methanol masers

C.J. Phillips,[1] R.P. Norris,[2] S.P. Ellingsen[1] and D.P. Rayner[1]
[1] *Department of Physics, University of Tasmania, GPO Box 252-21, Hobart, TAS 7001, Australia.*
[2] *CSIRO Australia Telescope National Facility, PO Box 76, Epping, NSW 2121, Australia.*

Accepted 19xx. Received 19xx

ABSTRACT

We have used the Australia Telescope Compact Array (ATCA) to search for 6.7-GHz methanol maser emission towards 87 galaxies. We chose the target sources using several criteria, including far-IR luminosities and the presence of known OH megamasers. In addition, we searched for methanol masers in the nearby starburst galaxy NGC 253, making a full spectral-line synthesis image. No emission was detected in any galaxies, with detection limits ranging from 25 mJy to 75 mJy. This is surprising, given the close association of OH and methanol masers in Galactic star-formation regions, and significantly constrains models of OH megamaser emission. This absence of maser emission may be a result of low methanol abundances in molecular clouds in starburst galaxies.

Key words: masers – ISM:molecules - galaxies:ISM - radio lines:galaxies.

1 INTRODUCTION

Extragalactic maser emission was first discovered in NGC 253 in the 1665- and 1667-MHz transitions of OH (Whiteoak & Gardner 1974) with a luminosity about 100 times greater than typical Galactic OH masers. In 1982 an OH "megamaser", a maser a million times more luminous than the most luminous Galactic OH masers, was discovered in Arp220 (IC 4553) (Baan, Wood & Haschick 1982). Since then more than 50 extragalactic OH sources (often collectively called megamasers, although some of them extend to lower luminosities) have been discovered (Baan 1993). These OH sources are characterised by broad emission lines (up to several 100 km s^{-1}) and stronger emission at 1667 MHz than at 1665 MHz. This is in contrast to Galactic OH masers in star-forming regions which have a typical velocity range of 10 km s^{-1} and emission stronger at 1665 MHz than at 1667 MHz.

The standard model of OH megamasers (typified by Arp220) is that low-gain amplification occurs in a molecular disc around the nucleus of the galaxy (Norris 1984). The gas is pumped by far-infrared radiation (Baan 1989) and amplifies the nuclear continuum emission.

The number of known extragalactic H_2O masers is smaller than the number of OH masers, and can be divided into two types. The first extragalactic H_2O maser was discovered in M33 (Churchwell et al. 1977). This has a luminosity similar to the brightest Galactic maser, W49. Over a dozen H_2O masers of a similar luminosity have been discovered in other galaxies, including NGC 253. In 1979 a new class of H_2O masers was discovered in NGC 4945 (dos Santos & Lépine 1979). The intrinsic brightness of NGC 4945 is about 100 times greater than W49. 15 similarly bright masers have since been discovered, and the strongest, TXFS2226-184, is 5000 times more luminous than W49, and seven orders of magnitude stronger than typical Galactic H_2O masers (Koekemoer et al. 1995). These H_2O megamasers occur within a few pc of the galactic nucleus (Claussen & Lo 1986; Greenhill et al. 1990). In the Claussen & Lo model the maser emission occurs in a dense disc of gas and dust close to the nucleus of the galaxy. The masers are believed to be collisionally pumped as a result of the gas being heated by X-rays (Neufeld, Maloney & Conger 1994; Neufeld & Maloney 1995).

OH and H_2O megamasers are extremely powerful astrophysical tools. For example, VLBI observations of the H_2O megamasers in NGC 4258 have given the strongest evidence yet for the existence of massive black holes in active galaxies. The masers in this galaxy clearly show a Keplerian rotation, indicating a central mass of $3.5{\times}10^7$ M$_\odot$ in a region less than 0.13 pc (Miyoshi et al. 1995; Greenhill et al. 1995). Similar results are being found in NGC 1068 and the Circinus galaxy (Greenhill et al. 1996; Greenhill et al. 1997).

Strong methanol emission in the 12.2-GHz ($2_0 - 3_{-1}$ E) and 6.7-GHz ($5_1 - 6_0$A$^+$) transitions is often found in regions of star-formation (Batrla et al. 1987; Menten 1991). VLBI observations show that the 12.2- and 6.7-GHz masers are often spatially coincident (Menten et al. 1992; Ellingsen 1995). These methanol transitions are also closely associ-

ated with OH, often coincident to within less than 1 arcsec (Caswell, Vaile & Forster 1995).

Interferometric imaging of these sources has shown that they are often located in lines or arcs, with a simple velocity gradient along the line (Norris et al. 1993, 1997; Phillips et al. 1996). Norris et al. (1997) interpret these sources as edge-on circumstellar discs around young massive stars.

Although ∼400 Galactic 6.7-GHz methanol masers have been found (Ellingsen et al. 1996 and references therein), only three extragalactic methanol masers are known, all in the Large Magellanic Clouds (Sinclair et al. 1992; Ellingsen et al. 1994b; Beasley et al. 1996). These masers are unremarkable and their intrinsic brightness is similar to Galactic methanol masers. Only one published search for 6.7-GHz methanol megamasers has been made, in which ten known OH and H_2O megamaser galaxies were searched for 6.7-GHz emission, but none was found (Ellingsen et al. 1994a). Given the close association of methanol and OH in Galactic masers, this is surprising.

We present here a survey of 87 galaxies for 6.7-GHz megamaser emission, covering a variety of different types of galaxies. We have also done full spectral-line imaging on the edge-on starburst galaxy, NGC 253, to detect either megamaser emission or else strong maser emission associated with star-formation regions.

2 OBSERVATIONS

2.1 NGC 253

The observations were made with the Australia Telescope Compact Array during an 11-h period on 1994 July 28 with the array in the 6A configuration, which gives 15 baselines ranging in length from 337 to 5939 m. A bandwidth of 8 MHz was used with the correlator configured to give 1024 spectral channels in each of two orthogonal linear polarizations. The typical system temperature of the antennae at 6.7-GHz is 120 K.

Two pointing centres were required to accommodate the large velocity spread across the galaxy (∼450 km s^{-1}) and its large angular size (20 arcmin compared with a primary beam FWHM of 8.4 arcmin). The positions used were (00:47:38.98, -25:16:13.2) and (00:47:27.39, -25:18:19.1) J2000, with central frequencies 6664 and 6660 MHz, respectively. The two pointing centres were each observed 11 times for 25 min over 11 h, interspersed with observations of the secondary calibrator 0023-263.

The data were calibrated and imaged using the Astronomical Image Processing System (AIPS). 1934-638 was used as the primary flux calibrator, with an assumed flux density of 3.93 Jy at 6.6 GHz. After the initial calibration, the spectral channels were averaged and a continuum image made. The centre of the galaxy was clearly detected in both images with a flux density of 220 mJy. These continuum images were then phase self-calibrated (improving the signal-to-noise ratio from 130 to 300) and the improved phase calibration applied to the un-averaged spectral-line data. Because the spectral resolution of 0.35 km s^{-1} is comparable to a typical FWHM of 0.5 km s^{-1} for Galactic masers (Ellingsen et al. 1996), the data were not Hanning smoothed. Two 825-channel spectral cubes (with a velocity span of 290 km s^{-1}) were made for each of the pointing centres. Each cube covered 256×256 arcsec with an angular resolution of 2.9×1.3 arcsec. Together the two cubes covered approximately the inner third of the galaxy.

2.2 Megamaser survey

Since methanol is likely to be abundant only in molecular-rich galaxies, which are typically *IRAS* sources, the source selection for this survey included only southern *IRAS* galaxies, with known redshifts, known 60 μm flux density, and declination < +20 (except Arp 220). No sources with z > 0.15 were considered. Preference was given to sources that satisfied one or more of the following criteria:

(i) known OH megamaser galaxy
(ii) known H_2O megamaser galaxy
(iii) 60 μm flux (S60) > 10 Jy
(iv) S60 (Jy) × z > 0.3
(v) $\log(L_\odot) > 12$.

The observations were made between 1996 May 28 and 1996 June 3 using the ATCA, with the array in the 750D configuration, with 10 baselines ranging in length from 30.6 to 719.4 m. A bandwidth of 16 MHz was used with the correlator configured to give 512 channels for two orthogonal linear polarizations.

87 sources were observed from the sample discussed above. Table 1 lists the observed sources and their selection criteria. Each source was observed for 1 h, with an observation of a secondary calibrator made before and after each source. Sources were observed as close to transit as possible to simplify data processing (as discussed below), although this meant some of the observed sources did not satisfy any of the selection criteria specified above (because of the uneven distribution of the sources on the sky).

There are several advantages in using an interferometer in stead of a single dish for spectral-line detection experiments.

• Single-dish observations are often made in "position-switch" mode, spending half the observing time at a reference position and creating a "quotient spectrum". This is not required for an interferometer, enabling the same sensitivity to be achieved in one quarter of the time.

• Interferometers are also less susceptible to variations in the bandpass, enabling longer integrations.

The disadvantages are that neither a scalar nor a vector average of interferometer data produces the same response as a single dish.

• A scalar average spectrum of the data (averaging the individual power spectra from each baseline and each integration period) produces a lower sensitivity to weak spectral features because of noise bias (Thompson, Moran & Swenson 1986), which appears as a positive baseline offset in the spectrum, but under which weak spectral features are submerged.

• A vector average of the data (adding the real and imaginary parts separately, after phase rotation to a suitable phase centre position) overcomes this problem, but the spectrum is restricted to an area the size of the synthesised beam of the interferometer, centred at the averaging phase-centre.

For many of the sources in the sample, the position of the centre of the Galaxy was not sufficiently well known to

guarantee that the maser would lie at the phase centre of the synthesised beam. Making spectral cubes of all sources observed was not practical and so, instead, we overcame this problem by making all observations close to transit, so that the synthesised beam was approximately 15 arcsec $\times$ 2 arcmin, elongated in a north-south direction. We then plotted a series of spectra each with a different phase centre. By making a series of seven plots with the phase centre shifted by 10 arcsec from east to west across the observed position, we are sensitive to emission from sources within $\pm$30 arcsec of the nominal galaxy position.

For normal interferometric observations the antenna-based gains and delays need to be determined before each observing session, by observing both a primary and secondary flux calibrator at each observing frequency. To maximize the efficiency of the search, we chose not to do a full amplitude calibration, but instead estimated gains based on the assumed secondary calibrator flux density, with additional calibration observations planned in the event of a detection. Since only rough delay calibration was used, we expect a 10-20 percent error caused by decorrelation during the observation. The amplitude calibration for most sources should be better than about 30 percent for most sources, though some may be only within a factor of two.

Basic calibration of the data was done using the AIPS software. A series of seven spectra, shifted in position as described above, was plotted for each source. To facilitate the detection of both narrow and broad emission, plots were produced with no smoothing, Hanning smoothing, and boxcar smoothing over 5 and 10 channels. The spectral resolution of the four smoothing schemes was 1.5, 3.0, 7.4 and 14.9 km s^{-1} respectively.

3 RESULTS

3.1 NGC 253

The rms noise was typically 23 mJy in each 0.35 km s^{-1}channel of the two image cubes. The peaks in each cube were found (the largest $\sim$ 130 mJy) and carefully checked for real emission in the image cube and u-v data. We did not detect any methanol emission. Plots of the spatial distribution of the peaks in the cube were consistent with noise, and there was no correlation with the position of the galaxy. The noise profile was nearly Gaussian but with slightly broader wings. Assuming a 5-σ detection threshold implies no 6.7-GHz methanol stronger than 107 mJy. Assuming a distance of 3.4 Mpc to NGC 253 (Huchtmeier 1972), the most luminous Galactic 6.7-GHz methanol maser, G340.78-0.10 (Norris et al. 1993), would have a flux density of 2.6 mJy in NGC 253. Thus our observations were not sensitive enough to detect Galactic-strength methanol masers in NGC 253, but would have detected masers 35 times stronger. The OH masers in NGC 253 are about 100 times stronger than those in our Galaxy, and so a corresponding experiment at OH wavelengths would have detected the masers at the 14-σ level.

3.2 Megamaser survey

All spectra for each source (phase-shifted and smoothed) were inspected visually for possible peaks in the data. A summary of the results is shown in Table 1. None of the 87 observed sources contained detectable 6.7-GHz emission. Assuming a detection threshold of 5 σ this gives a flux-density limit of 15 to 25 mJy for most sources, which is sufficient to detect almost all known OH and H_2O megamasers. The peak flux density of known OH and H_2O megamasers associated with these sources (as well as peak flux density limits) is also given in Table 1.

4 DISCUSSION

The 6.7-GHz $5_1 - 6_0$ A$^+$ transition of methanol is the second strongest masing transition observed in Galactic sources and is extremely common, which implies that it is relatively easy to produce the conditions needed for the molecule to produce maser emission. These masers are believed to exist in regions of star formation only and are closely related to OH masers. Most OH masers sources also show methanol emission, and vice-versa. Caswell et al. (1995) have shown that the OH and methanol emission is generally coincident to within 1 arcsec. This is interpreted as meaning that the OH and methanol masers require similar physical conditions. 23 known OH megamaser sources were included in the sample (see Table 1). Given the close association of Galactic OH and methanol masers it is surprising that methanol emission is not seen in any of these sources.

4.1 NGC 253

In NGC253, the OH maser emission has a flux density of 0.1 Jy. If the Galactic methanol/OH maser intensity ratio ($\sim$10) were to apply in NGC253, then we would expect to observe a 1-Jy methanol maser, which is ruled out by our observations.

Even if the methanol maser emission does not scale with the OH emission, the high star-formation rate in NGC253 might lead us to expect NGC253 to contain stronger methanol masers associated with star-formation than those in our own Galaxy. Our limit of 107 mJy rules out Galactic-type masers 35 times stronger than those in our own Galaxy.

4.2 Megamaser survey

Our sample of megamaser candidates encompasses most of the types of galaxies in which methanol megamasers might reasonably be expected to be found. Thus our failure to detect any suggests that 6.7-GHz methanol megamasers do not exist. This result has immediate implications for models of OH megamasers.

One such model suggests that OH megamasers represent a large collection of Galactic-type masers (Baan et al. 1982). As methanol is typically ten times stronger than OH in Galactic sources (Caswell et al. 1995) methanol should be observable with our sensitivity in some, if not all, OH megamaser galaxies. Thus these observations rule out this model of OH megamasers.

Table 1. The selected sample of galaxies

IRAS Name	Alias	Position (J2000) RA	Dec	OH Peak Flux (mJy)	H_2O Peak Flux (mJy)	z	*IRAS* 60μm Jy	Sel.[a] Crit.	RMS[b] Noise (mJy)	References[c]
00198−7926		00:21:54	−79:10:08			0.0724	3.2	o	14.3	
00335−2732		00:36:01	−27:15:34	<20		0.0691	4.4	z	9.1	52,53
00450−2533	NGC 253	00:47:33	−25:17:18	120	5000	0.001	759.0	hszw	16.6	1,3,13,15,16,27,29 33,38,46,52,56,59
01418+1651	III Zw 35	01:44:31	+17:06:09	240		0.0273	11.9	hsz	19.0	20,24,29,30,38,42,45 46,50,53,58,63
01458−2828		01:48:09	−28:14:02			0.1352	0.8	o	19.7	
02401−0013[d]	NGC 1068	02:42:41	−00:00:48	5	670	0.0038	186.0	o	30.0	10,15,18,56,59,60,61,62
02512+1446	Z 440-30	02:54:02	+14:58:15			0.031	7.7	o	21.0	
03317−3618	NGC 1365	03:33:36	−36:08:23	50	<210	0.0055	78.2	hsz	22.8	40,59,61
03359+1523		03:38:47	+15:32:54			0.035	5.8	o	18.5	
03540−4230[d]	NGC 1487	03:55:45	−42:22:07			0.0026	3.3	o	8.0	56
04189−5503	NGC 1566	04:20:00	−54:56:18	<32	<340	0.005	12.7	s	25.2	40,56,61
04191−1855	ESO 550-25	04:21:20	−18:48:39			0.0308	5.8	o	25.3	
05059−3734	NGC 1808	05:07:42	−37:30:46	<32	<300	0.0033	97.1	sz	34.2	40,52,59,61
05100−2425		05:12:09	−24:21:54	18		0.0338	4.1	h	13.6	46,52
05189−2524		05:21:01	−25:21:45	30		0.0415	13.9	hsz	14.6	24,40,52
05238−4602	ESO 253-3	05:25:18	−46:00:18			0.0407	2.8	o	1.9	
06035−7102		06:02:54	−71:03:12	<30		0.0796	5.0	lz	11.4	52
06076−2139		06:09:45	−21:40:22	<15		0.0374	6.3	o	10.8	52
06102−2949	ESO 425-13	06:12:12	−29:50:31	<40		0.0611	4.4	o	14.5	52
06206−6315		06:21:01	−63:17:23	<20		0.0917	4.0	lz	9.3	52
06219−4330		06:23:25	−43:31:45	<25		0.063	4.7	o	8.1	52
06259−4708	ESO 255-7	06:27:22	−47:10:37	<25		0.038	9.4	z	8.7	52
08014+0515	Mrk 1210	08:04:06	+05:06:50		160	0.013	1.8	w	22.7	54,61
08071+0509		08:09:48	+05:01:03	y[e]		0.0543	4.8	h	9.3	43
08520−6850		08:52:32	−69:01:54	<20		0.0463	5.8	o	23.8	52
09004−2031	ESO 64-11	09:02:46	−20:43:30	<15		0.0085	8.7	o	96.2	24,52
09149−6206	QSO0914-621	09:16:09	−62:19:29			0.0573	2.5	o	15.6	
10039−3338	ESO 374-32	10:06:07	−33:53:22	240		0.0337	9.1	hz	18.0	34,46,47,52,56,58,63
10173+0828		10:20:00	+08:13:34	100		0.0485	6.1	h	21.9	30,38,46
10221−2317	ESO 500-34	10:24:31	−23:33:12	<70		0.013	11.3	s	27.0	40
10257−4338	NGC 3256	10:27:52	−43:54:09	<30		0.0096	94.6	sz	78.8	40,52
11095−0238		11:12:03	−02:54:18			0.106	3.2	lz	12.7	
11143−7556		11:16:04	−76:12:53	<20		0.0054	47.7	s	48.4	40,52
11365−3727	NGC 3783	11:36:33	−37:27:42		<250	0.0107	3.4	o	23.6	61
11506−3851	ESO 320-30	11:53:12	−39:07:49	90	<850	0.010	34.2	hsz	22.2	17,29,38,40,46,52,53,56,61
11581−2033	ISZ 096	12:00:43	−20:50:07			0.0621	1.7	o	11.9	
12112+0305		12:13:46	+02:48:41	45		0.073	8.4	hlz	12.9	32,38,42,46,49,51,53
12232+1256	NGC 4388	12:25:47	+12:39:41	<20	<60	0.0085	10.9	s	25.7	16,51,61
12243−0036	NGC 4418	12:26:57	−00:52:50	7	<125	0.007	43.9	hsz	29.3	24,29,31,36,38,40,46 53,56,58,61
12294+1441	NGC 4501	12:31:59	+14:25:10		<160	0.0077	14.2	s	27.6	15,61
13001−2339	ESO507-70	13:02:52	−23:55:17	<18		0.0209	14.1	s	26.3	40,52
13025−4911	NGC 4945	13:05:26	−49:28:16		6200	0.0020	388.1	wsz	160.7	1,2,4,9,29,46,52,59,61
13225−4245	Centaurus A	13:25:28	−43:01:09	120	<580	0.0018	171.0	hsz	645.5	29,57,61
13335−2612		13:36:22	−26:27:30			0.1248	1.4	o	15.5	
13451+1232		13:47:33	+12:17:24	1.7		0.122	2.0	h	45.1	48
14092−6506	Circinus	14:13:10	−65:20:22		16000	0.0013	248.7	wsz	56.3	6,9,19,29,56,59,61,64
14147−2248		14:17:36	−23:02:02	<25		0.0794	2.4	o	11.2	52
14348−1447	GNH 35	14:37:38	−15:00:24			0.0824	6.8	lz	16.6	
14376−0004	NGC 5713	14:40:11	−00:17:20	<12		0.007	19.8	s	41.1	16,51
14378−3651		14:40:58	−37:04:25	<20		0.0682	6.5	lz	11.7	52
15107+0724	Zw 049.057	15:13:13	+07:13:35	13		0.012	21.6	hs	19.3	21,26,35,38,46,53
15247−0945		15:27:26	−09:55:57	y[e]		0.0400	4.7	h	13.2	44,46
15268−7757	ESO 22-10	15:33:36	−78:07:28	<25		0.0087	4.2	o	16.5	52
15322+1521	NGC 5953	15:34:32	+15:11:42		<90	0.0066	10.4	s	20.0	61
15327+2340	Arp220	15:34:57	+23:30:12	300	<200	0.0182	104.0	hsz	28.0	5,7,8,11,12,15,16,23 24,25,28,29,38,39,46 53,55,56,58
16164−0746		16:19:12	−07:54:03	<25		0.021	10.2	s	25.4	40

Table 1 – *continued*

IRAS Name	Alias	Position (J2000) RA	Dec	OH Peak (mJy)	H_2O Flux (mJy)	z	*IRAS* 60μm Jy	Sel.[a] Crit.	RMS[b] Noise (mJy)	References[c]
16330−6820	ESO 69-6	16:38:13	−68:26:43	<35		0.0456	7.2	z	121.4	52
16399−0937		16:42:40	−09:43:14	25		0.0267	8.5	h	16.8	22,46
16504+0229	NGC 6240	16:52:59	+02:23:59	<20	<90	0.0245	23.5	sz	13.4	24,29,40,61
17208−0014		17:23:21	−00:17:00	125		0.0428	34.1	hlsz	10.6	14,24,28,38,40,41,42 46,53,58
17260−7622		17:33:14	−76:24:48	<20		0.0181	4.2	o	18.1	52
17422−6437	IC 4662	17:47:06	−64:38:25	<12		0.0011	8.3	o	22.1	52
18093−5744	ESO 140-10	18:13:40	−57:43:38	<25		0.017	15.2	s	20.9	52
18293−3413		18:32:40	−34:11:26	<18		0.018	35.3	sz	41.2	40,52
18325−5926	Fair 49	18:36:59	−59:24:09	<32	<575	0.0192	3.2	o	20.7	4061
18401−6225	ESO 140-43	18:44:47	−62:21:57	<35	<290	0.0136	2.0	o	18.1	40,61
18421−5049	ESO 230-10	18:46:02	−50:46:30	<20		0.0177	5.1	o	15.9	52
18508−7815	QSO1850-782	18:58:33	−78:11:49			0.1618	1.1	o	11.3	
19115−2124	ESO 593-8	19:14:32	−21:19:04	<20		0.0495	6.2	z	17.6	52
19254−7245	Superantennae	19:31:21	−72:39:22	<40		0.0615	5.2	z	3.6	52
19297−0406		19:32:21	−04:00:06			0.0856	7.2	lz	14.1	
19393−5846	NGC 6810	19:43:34	−58:39:21	<25		0.006	18.1	s	20.2	40
20087−0308		20:11:23	−02:59:54			0.1033	4.6	lz	15.6	
20100−4156		20:13:30	−41:47:35	200	<3500	0.129	5.2	hlz	4.8	37,46,49,52,58,61,63
20414−1651		20:44:17	−16:40:14			0.0871	4.7	lz	11.5	
20491+1846	Z 448-16	20:51:26	+18:58:08	y[e]		0.0283	2.8	h	9.4	43
20550+1656	II Zw 96	20:57:24	+17:07:40	40		0.0362	13.1	hsz	9.2	21,24,38,46,53
20551−4250	ESO 286-19	20:58:27	−42:39:06	<30		0.0428	12.7	sz	11.6	40,52
21130−4446		21:34:15	−44:32:43	<20		0.0925	3.2	l	12.2	52
21219−1757	QSO2121-179	21:24:42	−17:44:46			0.113	1.1	o	8.7	
21330−3846	ESO 343- 13	21:36:11	−38:32:37	<35		0.0191	6.8	o	12.5	52
21453−3511	NGC 7130	21:48:19	−34:57:09	<20	<450	0.0161	16.7	s	24.7	40,52,61
22287−1917	ESO 602-25	22:31:25	−19:01:60	<25		0.025	5.8	o	15.7	51
22467−4906	ESO 239-2	22:49:40	−48:50:59	<20		0.0423	6.6	o	15.4	52
22491−1808		22:51:49	−17:52:24	15		0.0777	5.5	hz	10.5	51,46,49
23007+0836	NGC 7469	23:03:16	+08:52:26	<8	<60	0.0162	27.0	sz	15.6	24,40,59,61
23128−5919	ESO 148-2	23:15:47	−59:03:17	<22		0.0447	11.1	sz	17.8	40,52
23156−4238	NGC 7582	23:18:23	−42:22:11	<32	<265	0.0053	48.0	s	35.4	40,52,61
23230−6926		23:26:04	−69:10:16	<20		0.1062	3.7	lz	13.5	52

NOTES:
(a): The selection parameters satisfied by this source (see Section 2.2). s=S60>10; z=S60×z>0.3; l=logLIR>12; h=known OH megamaser; w=known H_2O megamaser; o=other *IRAS* galaxy.
(b): The quoted rms is after boxcar smoothing of five channels. The data were also inspected visually with no smoothing, Hanning smoothing and box-car smoothing of five and ten channels.
(c): 1=(Whiteoak & Gardner 1974); 2=(Whiteoak & Gardner 1975); 3=(Lépine & dos Santos 1977); 4=(dos Santos & Lépine 1979); 5=(Baan et al. 1982); 6=(Gardner & Whiteoak 1982); 7=(Baan & Haschick 1984); 8=(Norris 1984); 9=(Moorwood & Glass 1984); 10=(Claussen, Heiligman & Lo 1984); 11=(Norris et al. 1985b); 12=(Norris 1985a); 13=(Turner 1985); 14=(Bottinelli et al. 1985); 15=(Henkel, Wouterloot & Bally 1986); 16=(Unger et al. 1986); 17=(Norris et al. 1986); 18=(Claussen & Lo 1986); 19=(Whiteoak & Gardner 1986); 20=(Chapman et al. 1986); 21=(Bottinelli et al. 1986); 22=(Staveley-Smith et al. 1986); 23=(Baan et al. 1987b); 24=(Staveley-Smith et al. 1987); 25=(Baan & Haschick 1987); 26=(Baan, Henkel & Haschick 1987a); 27=(Ho et al. 1987); 28=(Henkel, Guesten & Baan 1987a); 29=(Norris et al. 1987); 30=(Mirabel & Sanders 1987); 31=(Bottinelli et al. 1987); 32=(Mirabel, Kazes & Sanders 1988); 33=(Nakai & Kasuga 1988); 34=(Kazes, Mirabel & Combes 1988); 35=(Martin et al. 1988a); 36=(Martin et al. 1988b); 37=(Stavely-Smith et al. 1989); 38=(Baan 1989); 39=(Diamond et al. 1989); 40=(Norris et al. 1989); 41=(Mirabel, Rodriguez & Ruiz 1989); 42=(Baan, Haschick & Henkel 1989); 43=(Bottinelli et al. 1989); 44=(Kazes, Mirabel & Combes 1989); 45=(Chapman et al. 1990); 46=(Haschick et al. 1990); 47=(Kazes et al. 1990); 48=(Dickey et al. 1990); 49=(Kazes & Baan 1991); 50=(Montgomery & Cohen 1992); 51=(Baan, Haschick & Henkel 1992); 52=(Staveley-Smith et al 1992); 54=(Braatz, Wilson & Henkel 1994); 55=(Lonsdale et al. 1994); 56=(Ellingsen et al. 1994a); 57=(van Langevelde et al. 1995); 58=(Randell et al. 1995); 59=(Nakai et al. 1995); 60=(Gallimore et al. 1996); 61=(Braatz, Wilson & Henkel 1996); 62=(Greenhill et al. 1996); 63=(Killeen et al. 1996); 64=(Greenhill et al. 1997);
(d): These sources were not part of the current survey, but were observed by Ellingsen et al. (1994a) and included for completeness.
(e): These sources have been detected, but only the isotropic luminosity has been published.

We also note that our result rules out another (unpublished) model for megamasers in which a massive black hole at the galactic nucleus gravitationally lenses normal masers in star-formation regions on the far side of the galaxy. Since Galactic OH masers are usually accompanied by much stronger methanol masers, this model predicts that we should detect methanol megamasers in a substantial fraction of the OH megamaser galaxies.

This result has implications for the "standard" model of megamaser emission (Norris 1984), in which low-gain maser amplification of a background source occurs in molecular clouds within the galactic disc. Within a megamaser galaxy, the maser path need not be confined to any one molecular cloud, but instead may encompass many different regions with widely varying conditions. Only those regions which have the right abundance, pump conditions, and velocity, will contribute to the intensity of the maser. However, this process is not critically dependent on any one condition (e.g. the precise value of optical depth to the pump), because the maser path will generally sample a wide range of conditions.

An OH megamaser galaxy has, by virtue of its OH emission, already demonstrated that it has a high column density of molecular material, aligned at a suitable velocity against a suitable input source to the maser amplifier, so that all the conditions for methanol megamaser emission are already satisfied provided that (a) the methanol abundance is sufficiently high, and (b) that somewhere along the line of sight, there exist suitable pumping conditions to invert the methanol population.

We now consider possible reasons for the absence of methanol megamasers.

• The methanol abundance may be too low in these galaxies to support masing on the scale needed for megamaser emission. However, Henkel et al. (1987b) detected methanol at millimetre wavelengths towards NGC 253 and IC 342, with abundances similar to those in our own Galaxy. This rules out a low methanol abundance as the reason for the lack of methanol megamasers.

• Methanol may not form on large scales. If the methanol abundance was not sufficiently high in the molecular clouds which constitute the maser amplifiers, we would not expect to see megamaser emission. Galactic methanol masers are seen only in star-formation regions and the molecules are generally thought to form on the surface of dust grains, and are released upon the destruction of the grain (Herbst 1991). If there were processes operating within molecular clouds which depleted the abundance of methanol, then methanol abundances sufficient for maser action might be confined to star-formation regions and not exist on the large scales needed to produce megamasers.

• Appropriate pumping conditions may not exist for methanol masers to operate on a sufficiently large scale. We consider this less likely because a) both OH megamasers and (Galactic) methanol masers are believed to be pumped by IR radiation, b) the widespread nature of methanol masers in star-formation regions suggests that it is relatively easy to pump methanol, c) as noted above, it is unlikely that the appropriate conditions do not occur anywhere along the masing path. However, we note that the methanol pumping mechanism is not yet fully understood, and it is possible that it requires special conditions, such as very high densities.

In this section, we have not considered implications of this result for H_2O megamasers, as the pump mechanisms for OH and methanol (probably IR) is significantly different from that of H_2O megamasers (collisionally pumped by X-ray-heated gas).

5 CONCLUSIONS

A survey of 87 *IRAS* galaxies for 6.7-GHz methanol masers detected no emission towards any of the galaxies. Our detection limits are sufficiently low to detect most known OH and H_2O megamasers. Our sample encompasses most of the types of galaxies in which we might expect to find methanol megamasers, and the sample size is large enough that we can reasonably conclude that methanol megamasers do not exist. This result has two significant implications:

• the absence of methanol megamasers rules out models for OH megamasers involving large numbers of HII regions similar to those in our galaxy.

• it suggests that OH megamasers are located in large molecular clouds in which the abundance of methanol is much lower than that of OH.

6 ACKNOWLEDGMENTS

The Australia Telescope is funded by the Commonwealth Government for operation as a National Facility managed by the CSIRO. This research used the SIMBAD data base, operated at CDS, Strasbourg, France and the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology.

REFERENCES

Baan W.A., 1989, ApJ, 338, 804
Baan W.A., 1993, in *Subarcsecond Radio Astronomy*, eds Davis, R.J. and Booth, R.S., Cambridge Univ. Press, Cambridge, U.K., 324
Baan W.A., Haschick A.D., 1984, ApJ, 279, 541
Baan W.A., Haschick A.D., 1987, ApJ, 318, 139
Baan W.A., Wood P.A.D., Haschick A.D., 1982, ApJ, 260, L49
Baan W.A., Henkel C., Haschick A.D., 1987a, ApJ, 320, 154
Baan W.A., van Gorkom J.H., Schmelz J.T., Mirabel I.F., 1987b, ApJ, 313, 102
Baan W.A. Haschick A.D., Henkel C., 1989, ApJ, 346, 680
Baan W.A., Haschick A., Henkel C., 1992, AJ, 103, 728
Batrla W., Matthews H.E., Menten K.M., Walmsley C.M., 1987, Nature, 326, 49
Beasley A.J., Ellingsen S.P., Claussen M.J., Wilcots E., 1996, ApJ, 459, 600
Bottinelli L., Gouguenheim L., Le Squeren A.M., Dennefeld M., Paturel G., 1985, IAU Circ., 4106
Bottinelli L., Gouguenheim L., Le Squeren A.M., Martin J.M., Dennefeld M., Paturel G., 1986, IAU Circ., 4231
Bottinelli L., Gouguenheim L., Le Squeren A.M., Martin J.M., Dennefeld M., Paturel G., 1987, IAU Circ., 4357
Bottinelli L., Gouguenheim L., Le Squeren A.M., Dennefeld M., Martin J.M., Paturel G., 1989, IAU Circ., 4928
Braatz J.A., Wilson A.S., Henkel C., 1994, ApJ, 437, L99
Braatz J.A., Wilson A.S., Henkel C., 1996, ApJS, 106, 51
Caswell J.L., Vaile R.A., Forster J.R., 1995, MNRAS, 277, 210
Chapman J.W., Cohen R.J., Pointon L., Staveley-Smith, L., Unger S.W., 1986, IAU Circ., 4180

Chapman J.M., Staveley-Smith L., Axon D.J., Unger S.W., Cohen R.J., Pedlar A., Davies R.D., 1990, MNRAS, 244, 281

Churchwell E., Witzel A., Pauliny-Toth I., Sieber W., Huchtmeier W., Roland J., 1977, A&A, 54, 969

Claussen M.J., Lo K.Y., 1986, ApJ, 308, 592

Claussen M.J., Heiligman G.M., Lo K.Y., 1984, Nature, 310, 298

Diamond P.J., Norris R.P., Baan W.A., Booth R.S., 1989, ApJ, 340, L49

Dickey J.M., Planesas P., Mirabel I.F., Kazes I., 1990, AJ, 100, 1457

dos Santos P.M., Lépine J.R.D., 1979, Nature, 278, 34

Ellingsen, S.P., 1995, PhD Thesis, University of Tasmania.

Ellingsen S.P., Norris R.P., Whiteoak J.B., Vaile R.A., McCulloch P.M., Price M.G., 1994a, MNRAS, 267, 510

Ellingsen S.P., Whiteoak J.B., Norris R.P., Caswell J.L., Vaile R.A., 1994b, MNRAS, 269, 1019

Ellingsen S.P., Von Bibra M.L., McCulloch P.M., Norris R.P., Deshpande A.A., Phillips C.J., 1996, MNRAS, 280, 378

Gallimore J.F., Baum S.A., O'Dea C.P., Brinks E., Pedlar A., 1996, ApJ, 462, 740

Gardner F.F., Whiteoak J.B., 1982, MNRAS, 201, 13P

Greenhill L.J., Moran J.M., Reid M.J., Gwinn C.R., Menten K.M., Eckart A., Hirabayashi H., 1990, ApJ, 364, 513

Greenhill L.J., Jiang D.R., Moran J.M., Reid M.J, Lo K.Y., Claussen M.J., 1995, ApJ, 440, 619

Greenhill L.J., Gwinn C.R., Antonucci R., Barvainis R., 1996, ApJ, 472, L21

Greenhill L.J., Ellingsen S.P., Norris R.P., Gough R.G., Sinclair M.W., Moran J.M., Mushotzky R., 1997, ApJ, 474, L103

Haschick A.D., Baan W.A., Schneps M.H., Reid M.J., Moran, J.M., Guesten R., 1990, ApJ, 356, 149

Henkel C., Wouterloot J.G.A., Bally J., 1986, A&A, 155, 193

Henkel C., Guesten R., Baan W.A., 1987a, A&A, 185, 14

Henkel C., Jacq T., Mauersberger R., Menten K.M., Steppe H., 1987b, A&A, 188, L1

Herbst, E., 1991, ApJ, 366, 133

Ho P.T.P., Martin R.N., Henkel C., Turner J.L., 1987, ApJ, 320, 663

Huchtmeier W., 1972, A&A, 17, 207

Kazes, I., Baan, W.A., 1991, A&A, 248, L15

Kazes I., Mirabel I.F., Combes F., 1988, IAU Circ., 4629

Kazes I., Mirabel I.F., Combes F., 1989, IAU Circ., 4856

Kazes I., Proust D., Mirabel L.F., Combes F., Balkowski C., Martin J.M., 1990, A&A, 237, L1

Killeen N.E.B., Staveley-Smith L., Wilson W.E., Sault R.J., 1996, MNRAS, 280, 1143

Koekemoer A.M., Henkel C., Greenhill L.J., Dey A., van Breugel W., Codella C., Antonucci R., 1995, Nature, 378, 697

Lépine J.R.D., dos Santos P., 1977, Nature, 270, 501

Lonsdale C.J., Diamond P.J., Smith H.E., Lonsdale C.J., 1994, Nature, 370, 117

Martin J.M., Bottinelli L., Dennefeld M., Gouguenheim L., Handa T., Le Squeren A.M., Nakai N., Sofue Y, 1988a, A&A, 195, 71

Martin J.M., Le Squeren A.M., Bottinelli L., Gouguenheim L., Dennefeld M., 1988b, A&A, 201, L13

Menten K.M., 1991, ApJ, 380, L75

Menten K.M., Reid M.J., Pratap P., Moran J. M., Wilson T.L., 1992, ApJ, 401, L39

Mirabel I.F., Sanders D.B., 1987, ApJ, 322, 688

Mirabel I.F., Kazes I., Sanders D.B., 1988, ApJ, 324, L59

Mirabel I.F., Rodriguez L.F., Ruiz A., 1989, ApJ, 346, 180

Miyoshi M., Moran J., Herrnstein J., Greenhill L., Nakai, N., Diamond P., Inoue M., 1995, Nature, 373, 127

Montgomery A.S., Cohen R.J., 1992, MNRAS, 254, 23P

Moorwood A.F.M., Glass I.S., 1984, A&A, 135, 281

Nakai N., Kasuga T., 1988, PASJ, 40, 139

Nakai N., Inoue M., Miyazawa K., Hall P., 1995, PASJ, 47, 771

Neufeld D.A., Maloney P.R., 1995, ApJ, 447, L17

Neufeld, D.A., Maloney, P.R., Conger S., 1994, ApJ, 436, L127

Norris, R.P., PASA, 1984, 5, 514

Norris R.P., MNRAS, 1985a, 216, 701

Norris R.P., Baan W.A., Haschick A.D., Diamond P.J., Booth R.S., 1985b, MNRAS, 213, 821

Norris R.P., Whiteoak J.B., Gardner F.F., Allen D.A., Roche P.F., 1986, MNRAS, 221, 51P

Norris R.P., Caswell J.L., Gardner F.F., Wellington K.J, 1987, ApJ, 321, L159

Norris R.P., Gardner F.F., Whiteoak J.B., Allen D.A., Roche P.F., 1989, MNRAS, 237, 673

Norris R.P., Whiteoak J.B., Caswell J.L., Wieringa M.H., Gough R.G., 1993, ApJ, 412, 222.

Norris R.P., Byleveld S.E., Diamond P.J., Ellingsen S.P., Ferris R.H., Gough R.G., Kesteven M.J., McCulloch P.M., Reynolds J.E., Tzioumis A.K., Takahashi Y., Troup E.R., Wellington K.J., 1997, ApJ, submitted

Phillips C.J., Norris R.P., Ellingsen S.P., McCulloch P.M., Reynolds J.E., Gough R.G., Tzioumis A.K., Gussie G.T., Lovell J.E.J., Wieringa M.H. 1996, Proceedings of 4th APT Workshop

Randell J., Field D., Jones K.N., Yates J.A., Gray M.D., 1995, A&A, 300, 659

Sinclair M.W., Carrad G.J., Caswell J.L., Norris R.P., Whiteoak J.B., 1992, MNRAS, 256, 33

Staveley-Smith L., Unger S.W., Cohen R.J., Chapman J.M., Pointon L., 1986, IAU Circ., 4248

Staveley-Smith L., Cohen R.J., Chapman J.M., Pointon L., Unger S.W., 1987, MNRAS, 226, 689

Staveley-Smith L., Allen D.A., Chapman J.M., Norris R.P., Whiteoak J.B., 1989, Nature, 337, 625

Staveley-Smith L., Norris R.P., Chapman J.M., Allen D.A., Whiteoak J.B., Roy A.L., 1992, MNRAS, 258, 725

Thompson A.R., Moran J.M., Swenson G.W., 1986, Interferometry and synthesis in radio astronomy, Wiley-Interscience, New York

Turner B.E., 1985, ApJ, 299, 312

Unger S.W., Chapman J.M., Cohen R.J., Hawarden T.G., Mountain C.M., 1986, MNRAS, 220, 1P

van Langevelde H.J., van Dishoeck E.F., Sevenster M.N., Israel F.P., 1995, ApJ, 448, L123

Whiteoak J.B., Gardner F.F., 1974, ApL, 15, 211

Whiteoak J.B., Gardner F.F., 1975, ApJ, 195, L81

Whiteoak J.B., Gardner F.F., 1986, MNRAS, 222, 513